

# Using the seismology of non-magnetic chemically peculiar stars as a probe of dynamical processes in stellar interiors

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**Abstract.** Chemical composition is a good tracer of hydrodynamical processes that occur in stars as they often lead to mixing and particle transport. By comparing abundances predicted by models and those observed in stars we can infer some constraints on those mixing processes. As pulsations in stars are often very sensitive to chemical composition, we can use asteroseismology to probe the internal chemical composition of stars where no direct observations are possible. In this paper I focus on main sequence stars  $\alpha$  Cen,  $\lambda$  Bootis, and HgMn stars and discuss what we can learn of mixing processes in those stars from seismology.

*Key words:* variable stars – diffusion

## 1. Introduction

Chemically peculiar stars (CP stars) are stars in which at least one but typically several elements are significantly over- or under-abundant with respect to what is considered a normal composition for such stars. In population I main-sequence stars this standard is the Sun.

Chemically peculiar stars come in many forms throughout the HR diagram, and the physical mechanism(s) responsible for those anomalies vary in different regions of the HR diagram. In giant stars for example episodes of deep convection mix matter that has undergone nucleosynthesis with matter from cooler regions unaffected by nuclear processes (see Busso et al. 1999 for example). In cool population I and population II stars, turbulent mixing may lead to the destruction of light elements such as lithium from the surface layers of the stars (Michaud & Charbonneau 1991). The Sun for example is depleted of lithium by more than two orders of magnitude. Accretion of material onto the surface of stars or mass loss by a stellar wind have also been shown as means to produce chemically anomalous stars (Venn & Lambert 1990; Proffitt & Michaud 1989). Finally, microscopic diffusion due to

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gravity and radiation pressure acting differently on each atomic species is another way to build abundance anomalies in some types of stars (see a recent review by Vauclair (2003) and references therein). In the following we will focus on diffusion and accretion as they are the mechanisms that are dominant in main sequence CP stars of low to intermediate mass.

The chemical anomalies observed at the surface of CP stars extend in their interior. The abundance profiles depend on the interplay of diffusion, of other processes promoting stratification such as accretion and of mixing processes. It is these abundance profiles that we may be able to probe by studying the pulsations of those stars. If the basic physical processes leading to the formation of inhomogeneities are modeled accurately, we can then use the information on internal composition provided by pulsations to put constraints on the mixing processes that oppose the changes in composition.

In what follows we will see how chemical anomalies and pulsations are connected more specifically in main-sequence A and B-type stars where we find a large variety of both CP and variable stars. We will consider only non-magnetic stars to avoid the complications posed by the largely unknown strength and geometry of the magnetic fields in stellar interiors. Constraints on mixing processes can only be inferred when the other processes leading to the evolution of the composition can be modeled with no free parameters. We will concentrate on Am and HgMn stars, main sequence A and B type stars respectively, in which diffusion is the governing process and on  $\lambda$  Bootis stars that are thought to be formed through accretion of metal depleted circumstellar matter.

## 2. Abundance stratification in main-sequence stars

The governing equation for the evolution of abundances in a star is

$$\frac{\partial X}{\partial t} = \left[ (D_i + D_T) \frac{\partial X}{\partial M} + (v_i + v_w + v_{\text{hydro}}) X \right] - \lambda_{\text{sink}} X + \lambda_{\text{source}}, \quad (1)$$

where  $X$  is the mass fraction of a species.  $D_i$  and  $v_i$  are the diffusion coefficient and velocity for that species,  $D_T$  is the turbulent diffusion coefficient,  $v_w$  is a velocity due to mass loss (if positive) or accretion (if negative),  $v_{\text{hydro}}$  is a velocity due to large scale motions of matter (meridional circulation f. ex.),  $\lambda_{\text{sink}}$  is a sink term (non zero at the surface in the case of mass loss), and  $\lambda_{\text{source}}$  is a source term (non zero at the surface in the case of accretion).

The important processes that lead to abundance stratification (and surface abundance anomalies) and the competing mixing mechanisms contribute differently in each star depending on its temperature, age, mass, and rate of rotation. Accretion on the other hand, when present, is an external process practically independent of the properties of the star.

## 2.1 *Mixing*

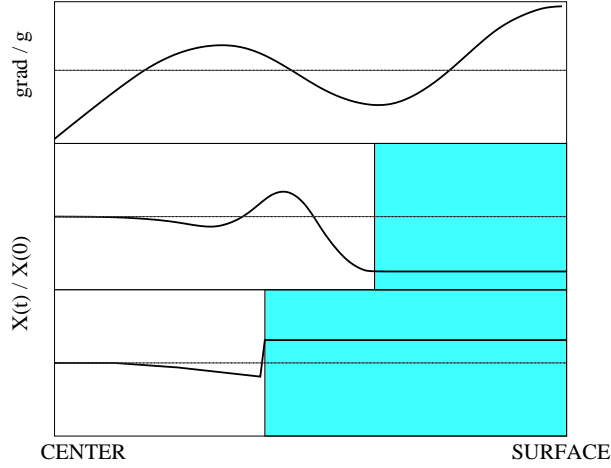
Several processes lead to mixing in stars, in some cases through large scale motion that transport matter throughout the interior, in other cases through local motions such as turbulence. The most common and most important of the mixing mechanisms is convection. In so-called *standard* stellar models, convection is typically the only mixing mechanism considered. Amongst the other mixing processes the most important are convection overshoot and rotational induced mixing. Rotation leads to large scale motions meridional circulation but also to turbulent motions induced by rotational shear or as the result of the transfer of angular momentum from the core toward the surface. In stellar models turbulent mixing due to convection or other forms of turbulent motions is accounted for through the turbulent diffusion coefficient ( $D_T$  in Eq. 1). In the models discussed below,  $D_T$  for convection is arbitrary but must be very large, while the functional form for the combined effect of all other mixing mechanisms is an ad hoc power law (Richer et al. 2000).

Convection typically occurs in regions of partial ionization of HI and HeI at around 10 000 K and of HeII at around 40 000 K. In non-magnetic stars with surface temperature of less than 10 000 K, the outer regions of the star, including the photosphere, are convective. The HI+HeI and HeII convection zones are expected to be linked by convection overshoot. As a result the whole outer envelope of these stars are completely mixed. Mixing is also expected to extend below the HeII convection zone because of overshoot or turbulence. The region in which the star is fully mixed extends to a certain depth. This mixed region is named the Superficial Mixed Zone (SMZ) in the remainder of this paper. The extent of the SMZ may be determined by seismology.

In cool stars, the photospheric abundance measured spectroscopically are identical to the abundances at the deepest point of the SMZ. Surface abundances are determined by particle processes that occur relatively deep in the interior. In stars hotter than 10 000 K, the outermost regions are not convective and therefore may not be mixed. Stratification can therefore occur in the photosphere. As a result, the photospheric abundances can be completely different from the abundances in the star's interior.

## 2.2 *Diffusion*

Chemical species drift relative to each other as the net forces acting on each species vary depending on their atomic properties. Essentially, it is the competition between gravity and radiation pressure that determines if an element will levitate toward the surface or sink toward the center of the star. While gravity is essentially constant in the outer parts of stars, radiation pressure goes through peaks and troughs depending on the local temperature and density. Where radiation pressure is larger than gravity, an element will drift outward, but will sink if gravity is larger. Fig. 1 shows a cartoon that illustrates the effect of diffusion on the chemical profiles and the effect of the depth of the SMZ on surface abundances. In the middle



**Figure 1.** The top panel is a cartoon representation of the ratio between the acceleration due to radiative pressure ( $g_{\text{rad}}$ ) and the gravitational acceleration ( $g$ ), where the horizontal dotted line shows a ratio of one. The middle panel shows the evolution of the abundance profile as the result of the  $g_{\text{rad}}/g$  profile shown above. The shaded region on the right is the Superficial Mixed Zone (SMZ) in which the abundance is homogenized by mixing. The bottom panel shows the evolution of the same element but for a deeper SMZ.

panel, the base of the SMZ occurs where gravity is larger than radiation pressure so the abundances in the SMZ are lower than initially. In the bottom panel, the deeper SMZ yields an increase in the surface composition but a smaller anomaly due to the larger mass of the SMZ.

The effect of diffusion on abundances can be calculated rather accurately from first principles. As a result, stars in which diffusion is the dominant process in creating abundance gradients are very useful tools to study mixing processes.

### 2.3 Accretion

Accretion does not depend directly on intrinsic properties of the accreting star but the material falling on the surface of the star must be mixed (diluted) in the entire SMZ. The composition in the mixed zone evolves on a time scale defined by the ratio of the mass of the mixed zone to the accretion rate ( $\tau = M_{\text{SMZ}}/\dot{M}$ ; neglecting here the effect of other processes at the base of the mixed zone). The depth in the star that the accreted material will reach depends on the depth of the SMZ, but also on the advection of the accreted matter in the star at a velocity of  $v = \dot{M}/4\pi\rho r^2$  (Charbonneau 1991).

Given a large enough rate of accretion (i.e. a short  $\tau$  compared to the evolution timescale), the abundances in the SMZ will be identical to those of the accreted matter. Once the accretion episode ends the signature of accretion rapidly disap-

pears (see detailed models in Turcotte & Charbonneau 1993). The abundance profiles will depend on the SMZ, on  $\dot{M}$ , and on the cumulative mass of the accreted material. None of which can be measured directly. As a result it may be difficult to find the depth of the SMZ uniquely for a given star.

### 3. Composition anomalies and their effect on pulsations

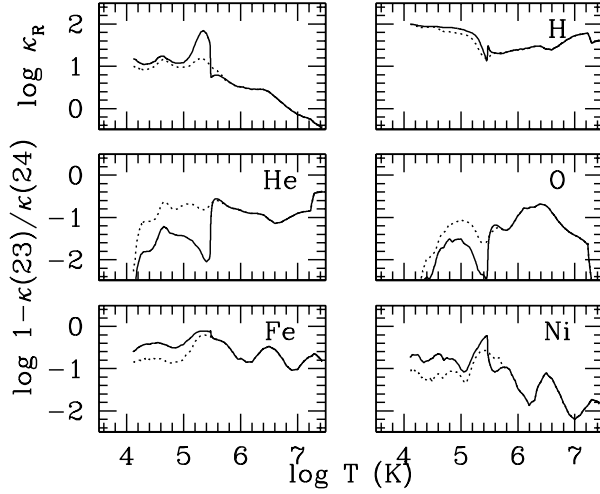
Different elements dominate the opacity at different depths in a star. Hydrogen and helium contribute most of the opacity at low temperature, iron dominates in hotter regions. In CP stars, the opacity profile will be different than in chemically homogeneous stars. The opacity might be smaller if the elements that dominate at a given temperature become less abundant, and inversely, might increase elsewhere as some elements accumulate where they play an important role.

In Fig. 2, the contribution of several elements to the opacity is shown in the case of a chemically homogeneous star of solar composition and in a star in which the abundances have been changed by diffusion. One can notice that the contributions of helium and of CNO have been reduced in the outer regions of the star while the contributions of iron-peak elements have increased. As a result, the driving due to helium is smaller in stars with diffusion than in normal stars, while the driving due to heavy elements is enhanced.

In stars in which accretion is ongoing, the effect on driving will be determined by the content of the accreted material and the depth in the star reached by the accreted material. In  $\lambda$  Bootis stars, the driving due to helium will be unchanged as helium is expected to be present in the accreted material and the helium driving region is inside the surface convection zone. The driving due to heavy elements will be changed only in certain circumstances.

### 4. Inference of mixing processes in CP stars

The ideas above have been applied to three types of chemically peculiar stars of the main sequence, the A-type Am and  $\lambda$  Bootis stars, and the B-type HgMn stars. Although similar in many ways these three types of stars are nonetheless different in important ways: When variable, Am and  $\lambda$  Bootis stars are delta Scuti type pulsators (p-modes driven by helium) while pulsating late-type B stars are g-modes excited by the opacity of heavy elements; Am and HgMn stars are slowly rotating while  $\lambda$  Bootis stars are moderately rapid rotators; and, finally, because of differences in the position of convection zones, the photospheric composition of Am and  $\lambda$  Bootis stars is the same as that of the driving region while it's not the case for HgMn stars because of diffusion in their atmosphere. The expected differences between these three types of stars are illustrated in Fig. 3.

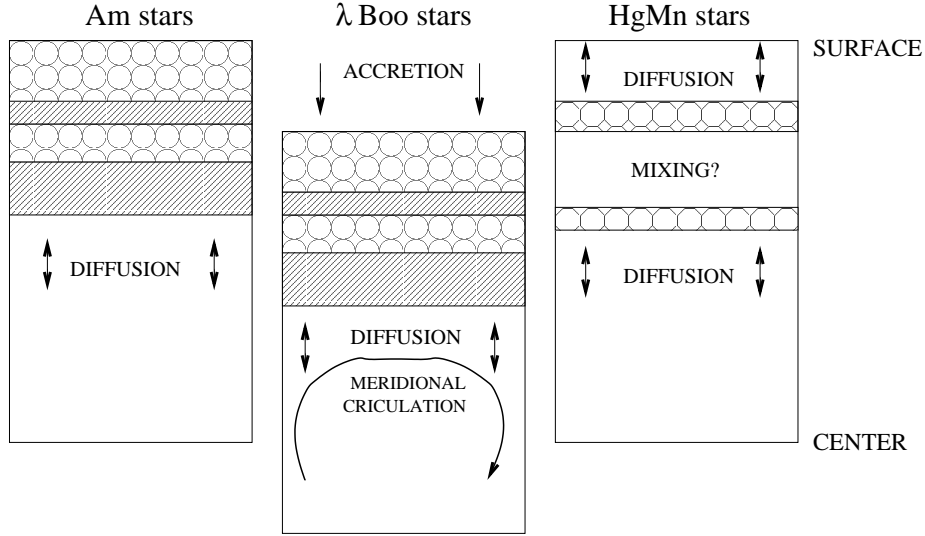


**Figure 2.** The relative contribution of individual elements to the Rosseland mean opacity is shown for 5 elements when the chemical composition is uniformly solar (dotted line) and when diffusion as occurred (solid line). The top left panel shows the logarithm of the Rosseland mean opacity in both cases. In the five other panels the logarithm of the ratio of the opacity including all elements in the star ( $\kappa(24)$ ) and the opacity calculated without the contribution of the element labeled ( $\kappa(23)$ ) is plotted. If an element provides all the opacity, then the curve for that element would reach one. The model shown is a  $4 M_{\odot}$  star model of 100 Myr (see Turcotte & Richard 2005, submitted).

#### 4.1 Application to Am stars

Models of non-rotating A stars were computed to test whether variable Am stars can be driven by the opacity of helium as in  $\delta$  Scuti stars (Turcotte et al. 2000). As suggested in Fig 2, as the helium settles out of the driving region as a result of diffusion the driving in Am stars is much lower than in chemically normal stars. As the helium driving region is inside the superficial convection, and thus inside the SMZ, the level of depletion of helium in the driving region is a direct function of the depth at which the SMZ extends, the deeper is the SMZ the higher the driving will be.

The blue (hot) edge of the instability zone for Am stars is in direct relation with the abundance of helium in the driving region as is shown in Fig. 4. Therefore, we can infer the depth of mixing from the instability region for Am stars. The boundary of the zone has not been explored in detail yet, partly because of the computational cost to do so. An additional difficulty is that the initial helium content of individual Am stars need not be identical and so the depth of mixing may not be a unique solution for all variable Am stars. Nevertheless, the depth of mixing found through seismology is consistent with what was found from modeling the surface composition (Richer et al. 2000).

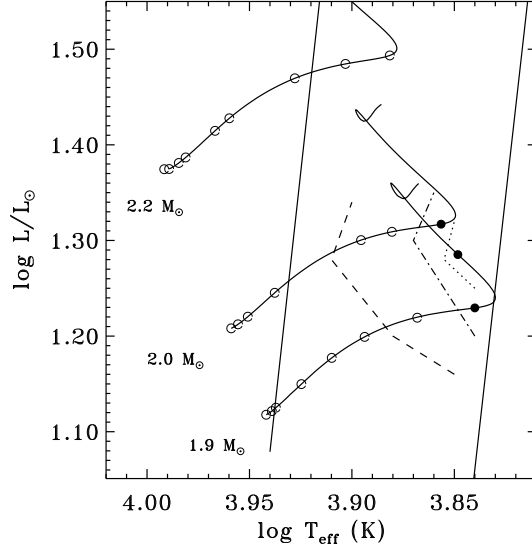


**Figure 3.** The cartoons (not to scale) illustrate the expected processes important in the evolution of the abundances of the three types of stars discussed in the paper. The regions filled with circles represents convection zones, the regions filled by oblique lines are non convective regions but otherwise mixed by other turbulent processes. The presence or absence of non-convective mixed regions in HgMn stars is not known. The deeper convection zone in HgMn stars appears only when iron-peak elements have accumulated in that region as the result of diffusion.

#### 4.2 Mixing and accretion in $\lambda$ Bootis stars

In the accretion model the light elements (H, He, CNO) in the SMZ are replenished by the infalling gas while most other elements are depleted by a factor of 10 in the accreting matter (Turcotte & Charbonneau 1993). As a result, one would not expect to see any measurable effect on the pulsations of  $\lambda$  Bootis stars in comparison to  $\delta$  Scuti stars if the SMZ is not significantly deeper than the surface convection zone of normal A stars. If, however, the SMZ extends significantly deeper, to the depth at which the opacity of heavy elements drive pulsations, an observable signature might be generated. Fig. 5 shows the relative change in frequency for radial modes ( $\ell = 0$ ) of radial order ( $n$ ) of 1 to 14 with respect to a chemically homogeneous model. We see that the differences are significant only if the chemical anomalies extend to a depth where the low metallicity of the accreted matter can make a large difference in the opacity ( $\log T > 5.2$ ). Models of Am stars suggest this should be the case, and as  $\lambda$  Bootis stars are faster rotators one may expect more mixing in  $\lambda$  Bootis stars than in Am stars.

Unfortunately, using frequencies to learn about the structure of  $\delta$  Scuti type stars as yet to be fruitful due to problems in mode identification and in dealing with rotation theoretically. Consequently, relying on the small frequency differ-



**Figure 4.** The HR diagram shows the approximate boundaries of the classical instability strip (oblique lines), the evolutionary paths of 1.9, 2, and  $2.2 M_{\odot}$  stars undergoing diffusion. The filled circles represent models where at least one unstable pulsation mode was found, the open circles show models that are stable. The three other lines show the approximate boundaries of the instability region for variable Am stars when the SMZ is shallow (dotted line), best fit (dash-dotted), or deep (dashed).

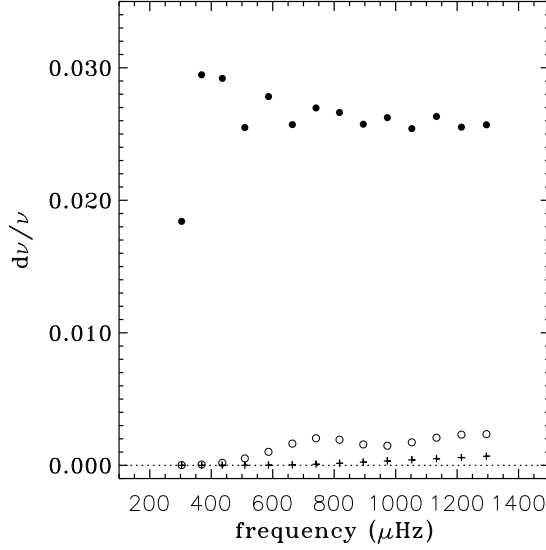
ences between the different models to infer the depth of the SMZ promises to be challenging.

#### 4.3 What is the matter with HgMn stars?

In pulsating B stars the driving is due to iron-peak elements (Pamyatnykh 1999). As HgMn stars are slowly rotating, the current theoretical expectation is that diffusion will occur in the interior as it does in the atmosphere (as the large abundance anomalies measured there attest). Models show that diffusion leads to an accumulation of iron-peak elements in the driving region. The increase in abundance of those elements naturally leads to an increase in opacity, which in turn leads to an enhanced driving. Fig. 6 shows the logarithmic opacity gradients for models of a  $4 M_{\odot}$  where the depth of the SMZ is varied. The increase of the peak at  $\log T \approx 5.2$  leads to an increase in the derivative of these opacity gradients which means that the driving does increase (see Shibahashi in these proceedings).

However, HgMn stars are not known to be variable whereas chemically normal stars of the same mass and evolutionary state are variable (those are the Slowly Pulsating B stars). The disagreement between the models and observations suggest





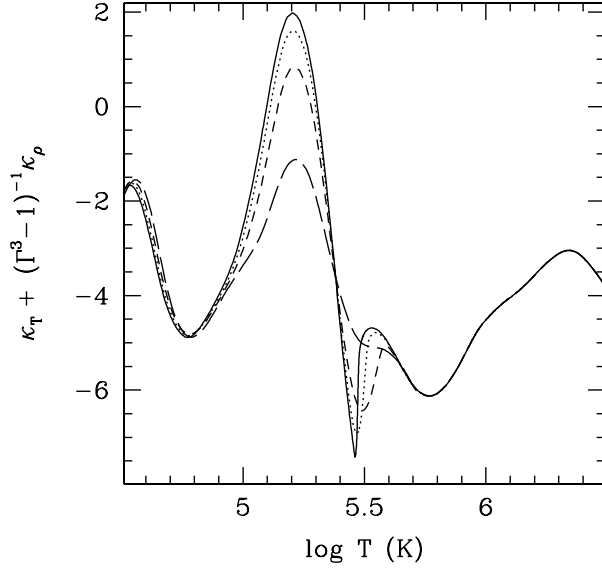
**Figure 5.** The relative difference in frequencies of radial modes of order 1 to 14 for models that are metal poor (except for CNO and S) to a depth where the temperature is  $\log T = 4.4$  (crosses),  $\log T = 5.0$  (open circles), and  $\log T = 5.8$  (filled circles) with respect of a chemically homogenous model are shown at the frequency of the reference model. The SMZ in the last model is  $10^6$  more massive than in the first.

that the models are deficient in some ways. A solution may come from introducing new physics in the models such as selective mass loss, but another possibility may simply be that the models are not accurate enough in the superficial regions. Indeed, the models discussed here assume for reasons of numerical stability that the stars are fully mixed from the photosphere to a depth past the mode driving region which is not realistic (Turcotte & Richard 2005, submitted). Only through further modeling combined with seismic data will we establish whether HgMn stars are really stable or variable at very low amplitude and what implication, if any, this has on dynamical processes occurring in these stars.

## 5. Conclusions

Using variability to infer mixing is especially useful in stars for which surface abundances is not a good indicator of internal composition, such as HgMn stars, and, to a certain degree,  $\lambda$  Bootis stars. In Am stars on the other hand, variability is an indicator of the abundance of helium, which is useful as it cannot be seen in spectra of these stars.

Much more work is required to refine this tool. At this time only the depth of the superficial region where abundances are homogeneous (the SMZ) can be



**Figure 6.** The sum of the logarithmic derivatives of opacity ( $\kappa_T = d \log \kappa / d \log T$ ,  $\kappa_\rho = d \log \kappa / d \log \rho$ ) is shown for four  $4 M_\odot$  models with more or less mixing versus the temperature in the star. The peak at around  $\log T = 5.2$  is due to the opacity of iron-peak elements. It is larger in models where mixing is lower and abundance anomalies are allowed to be larger. The pulsations are driven in regions where  $d/dr[\kappa_T + \kappa_\rho/(\Gamma_3 - 1)] > 0$ .

constrained in Am stars. The exact processes that lead to that mixing cannot be isolated nor can the exact profile of the turbulent diffusion coefficient be determined. Nevertheless, this tool remains our best hope to study the internal chemical composition of stars of the upper main-sequence as models improve and as the data from MOST, CoRoT and other missions hopefully provide us with low amplitude modes in Am,  $\lambda$  Bootis, and HgMn stars.

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